Modeling of Absorption and Scattering of IR Laser Radiation by LPP Targets

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Formulation of the problem

•Tendency to use of pre-conditioned targets in LPP EUV sources requires advanced models for simulations.
•One of the key aspects – modeling of laser reflection, absorption and transmission within the source region.
•Advanced geometrical optics approximation is proposed for solving this problem. It is supplemented with multilayer optical coverings approach, which is used close to critical density.

Geometrical optics approximation

We assume, that characteristic dimension of the medium is much greater than the laser wavelength, and from Maxwell equations for the case of conductive isotropic media with weak absorption and without magnetic properties one gets the following equations [1,2]:

$$\begin{cases} \dfrac{d\vec{r}}{d\tau} = n\vec{s}, \\ \dfrac{d(n\vec{s})}{d\tau} = \dfrac{1}{2}\nabla n^2, \\ \dfrac{dP}{d\tau} = -n\mu P. \end{cases}$$

Here:
τ is the parameter connected with phase by the expression $d\varphi = \frac{2\pi}{\lambda} n^2(\vec{r})d\tau$;
$\vec{s}$ is the unit vector along the ray;
$n = \mathrm{Re}\sqrt{\varepsilon}$ is the refractive index of plasma;
P is the power along the ray;
$\mu = \frac{2\pi}{\lambda}\mathrm{Im}\sqrt{\varepsilon}$ is the absorption coefficient;
λ is the wavelength of laser;
ε is the complex permittivity.

One-dimensional multilayer model

In this model we exactly solve the Helmholtz equation for medium consisting of thin flat homogeneous layers with constant permittivity [3].

S-polarization

$$\frac{\partial^2 E_y}{\partial z^2} + \frac{\omega^2}{c^2}\left(\varepsilon(z) - \sin^2\vartheta\right)E_y = 0$$

$$E_m(z_{m+1}) = E_{m+1}(z_{m+1})$$

$$\left.\frac{\partial E_m(z)}{\partial z}\right|_{z=z_{m+1}} = \left.\frac{\partial E_{m+1}(z)}{\partial z}\right|_{z=z_{m+1}}$$

P-polarization

$$\frac{\partial^2 B_y}{\partial z^2} + \frac{\omega^2}{c^2}\left(\varepsilon(z) - \sin^2\vartheta\right)B_y - \frac{\partial \ln\varepsilon(z)}{\partial z}B_y = 0$$

$$B_m(z_{m+1}) = B_{m+1}(z_{m+1})$$

$$\left.\frac{\partial B_m(z)}{\partial z}\right|_{z=z_{m+1}} = \frac{\varepsilon_m}{\varepsilon_{m+1}}\left.\frac{\partial B_{m+1}(z)}{\partial z}\right|_{z=z_{m+1}}$$

Ansatz: $F_m(z) = f_m^+ e^{ik_m(z-z_m)} + f_m^- e^{-ik_m(z-z_m)}$,
where $F_m(z)$ is either $E_m(z)$ or $B_m(z)$, $k_m = \frac{\omega}{c}\sqrt{\varepsilon_m - \sin^2\vartheta}$.
Boundary conditions: $f_0^+ = 1$, $f_{N_m}^- = 0$.
$\Rightarrow$ Closed system of linear algebraic equations.

The absorbed energy is defined by $Q = P\frac{\omega}{c}\mathrm{Im}\,\varepsilon_m \int_{z_m}^{z_{m+1}} \left|\vec{E}(z)\right|^2 dz$.

In the case of P-polarization $E_x(z) = -\frac{ic}{\varepsilon\omega}\frac{\partial B_y}{\partial z}, E_z(z) = -B_y \sin\frac{\vartheta}{\varepsilon}$.

Plasma permittivity calculation

For permittivity of non-relativistic Maxwellian plasma one can get [4]:

$$\mathrm{Re}\,\varepsilon = n^2 - \left(\frac{c}{2\omega}\mu\right)^2 = 1 - \frac{\omega_p^2}{\omega^2 + \nu_{ei}^2}$$

$$\mathrm{Im}\,\varepsilon = \frac{c}{\omega}n\mu = \frac{\omega_p^2\nu_{ei}}{\omega(\omega^2 + \nu_{ei}^2)}$$

$$\nu_{ei} = 9\cdot 10^{-11}\frac{Z_0 n_e}{T_e^{3/2}}\Lambda$$

Here
T_e is the electron temperature (eV);
n_e, n_i are the electron and ion densities (cm^{-3});
$Z_0 = n_e / n_i$ is the mean ionization;
Λ is the Coulomb logarithm;

$$\omega_p = \sqrt{\frac{4\pi e^2 n_e}{m_e}} \approx 5.64\cdot 10^4\sqrt{n_e}$$ is the plasma frequency.

For absorption in non-evaporated target we use experimental data for electric conductivity and its extrapolation to high temperature limit [5].

BELINE code: numerical algorithm

We assume gradient of n^2 and $n\mu$ to be constant [1,2] within a hydrodynamic cell. Then

$$n\vec{s}(\tau) = (n\vec{s})_0 + \frac{1}{2}\nabla n^2\tau$$

$$\vec{r}(\tau) = \vec{r}_0 + \int_0^\tau n\vec{s}(\tau_1)d\tau_1 = \vec{r}_0 + (n\vec{s})_0\tau + \frac{1}{4}\nabla n^2\tau^2$$

$$n\mu(\tau) = (n\mu)_0 + \nabla(n\mu)\cdot(\vec{r}(\tau) - \vec{r}_0) = (n\mu)_0 + \nabla(n\mu)\cdot(n\vec{s})_0\tau + \nabla(n\mu)\cdot\nabla n^2\frac{\tau^2}{4}$$

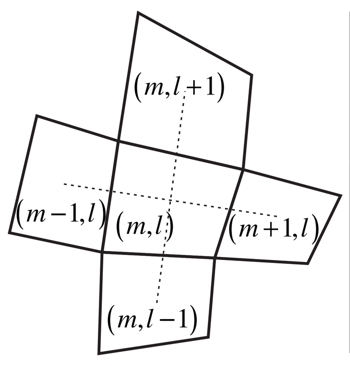
$$P(\tau) = P_0\exp\left(-\int_0^\tau n\mu(\tau_1)d\tau_1\right) = P_0\cdot\exp\left(-(n\mu)_0\tau - \nabla(n\mu)\cdot(n\vec{s})_0\frac{\tau^2}{2} - \nabla(n\mu)\cdot\nabla n^2\frac{\tau^3}{12}\right)$$

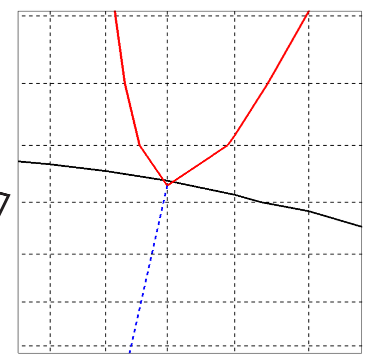
For gradient calculation the following approximation is used:

$$\left(\frac{\partial f}{\partial r}\right)_{m,l} = \frac{f_{m+1,l} - f_{m-1,l}}{\Delta l_{m+1,l,m-1,l}}\frac{r_{m+1,l} - r_{m-1,l}}{\Delta l_{m+1,l,m-1,l}} + \frac{f_{m,l+1} - f_{m,l-1}}{\Delta l_{m,l+1,m,l-1}}\frac{r_{m,l+1} - r_{m,l-1}}{\Delta l_{m,l+1,m,l-1}}$$

$$\left(\frac{\partial f}{\partial z}\right)_{m,l} = \frac{f_{m+1,l} - f_{m-1,l}}{\Delta l_{m+1,l,m-1,l}}\frac{z_{m+1,l} - z_{m-1,l}}{\Delta l_{m+1,l,m-1,l}} + \frac{f_{m,l+1} - f_{m,l-1}}{\Delta l_{m,l+1,m,l-1}}\frac{z_{m,l+1} - z_{m,l-1}}{\Delta l_{m,l+1,m,l-1}}$$

$$\Delta l_{m,l,m',l'} = \sqrt{\left(r_{m,l} - r_{m',l'}\right)^2 + \left(z_{m,l} - z_{m',l'}\right)^2}$$

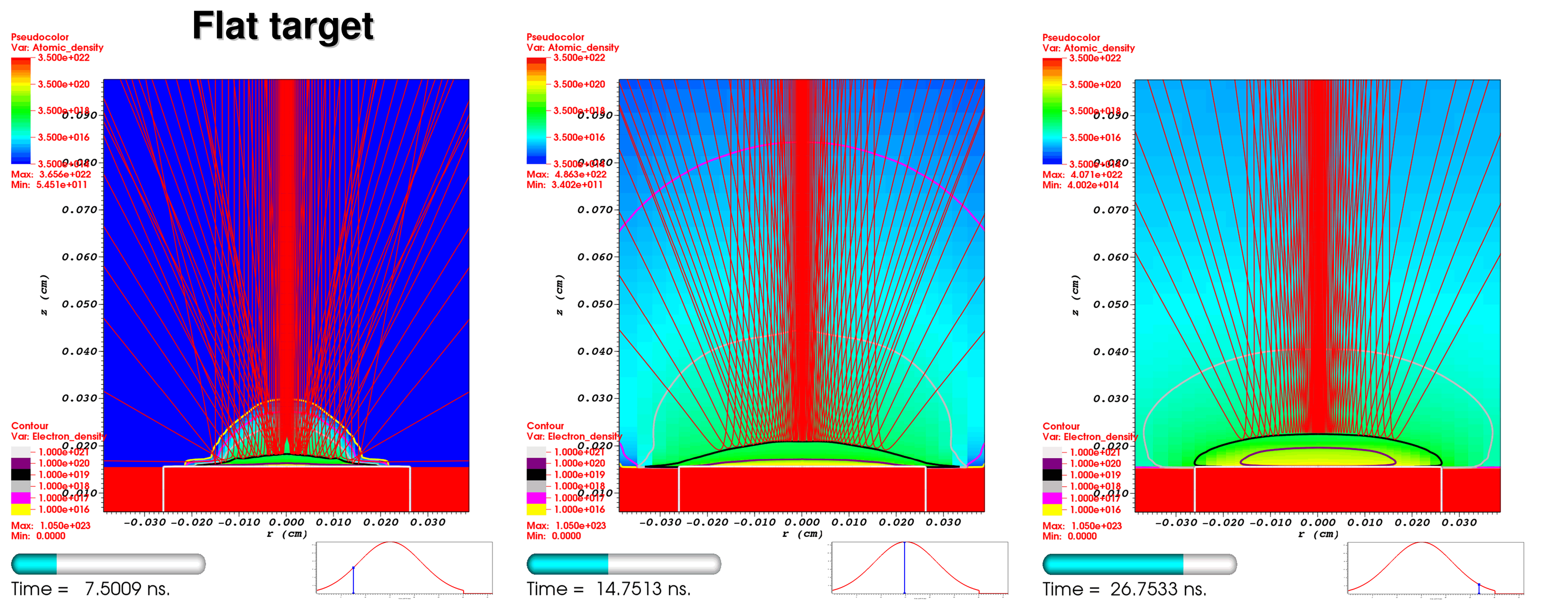




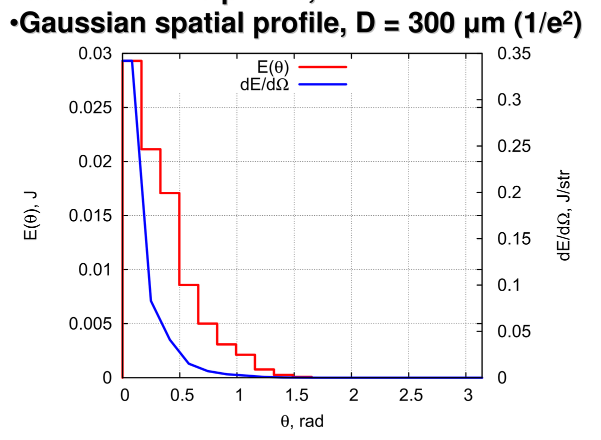
In geometrical optics algorithm we solve equations and follow the ray from cell to cell while it has not crossed grid borders. Then we take another ray. In the end of ray tracing we get power deposition in every cell. When the ray have got into the cell with close to critical electron density we reflect it and reduce power on it in accordance to solution of Helmholtz equation [3].

Simulation results: postprocessing of RZLINE output data

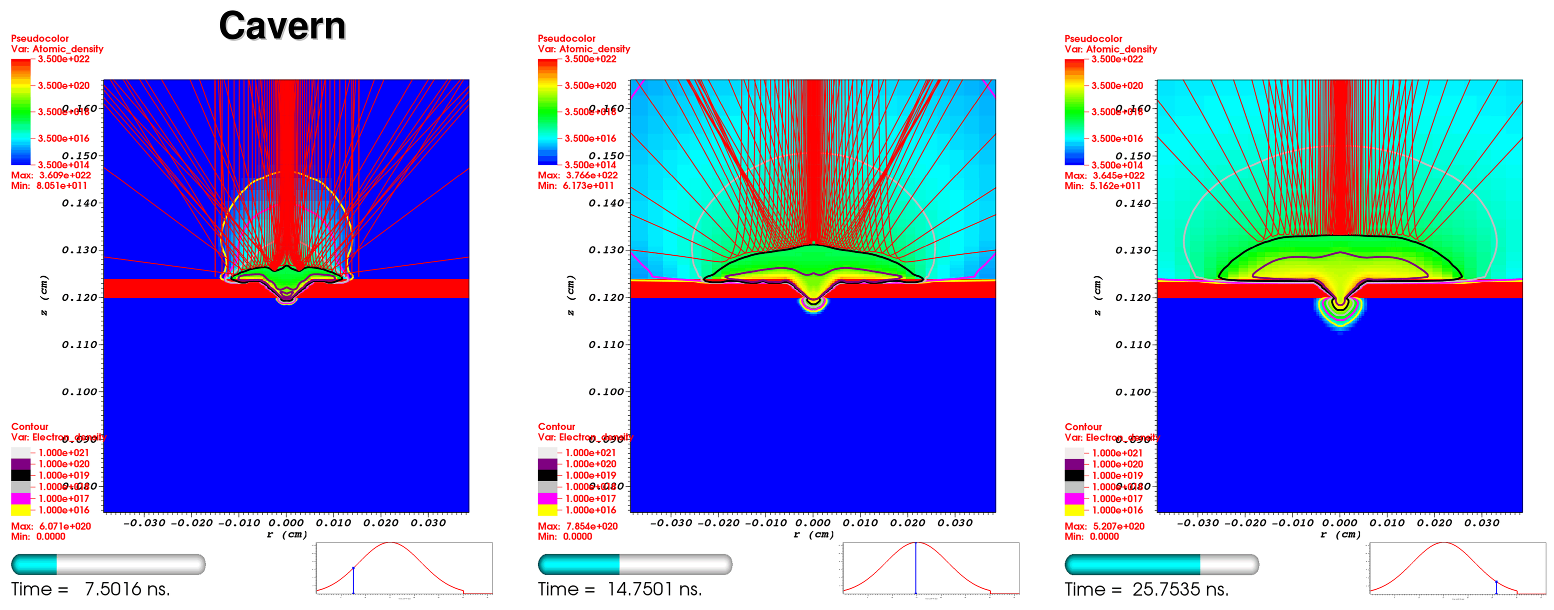
Flat target



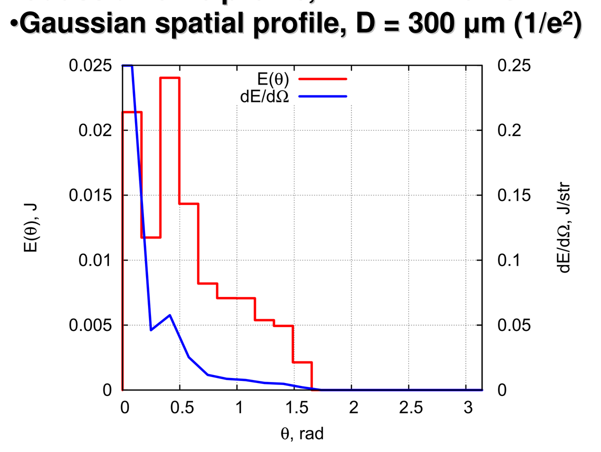
Target material – tin
CO_2 laser, 0.2 J:
•Gaussian time profile, FWHM = 15 ns
•Gaussian spatial profile, D = 300 μm (1/e²)



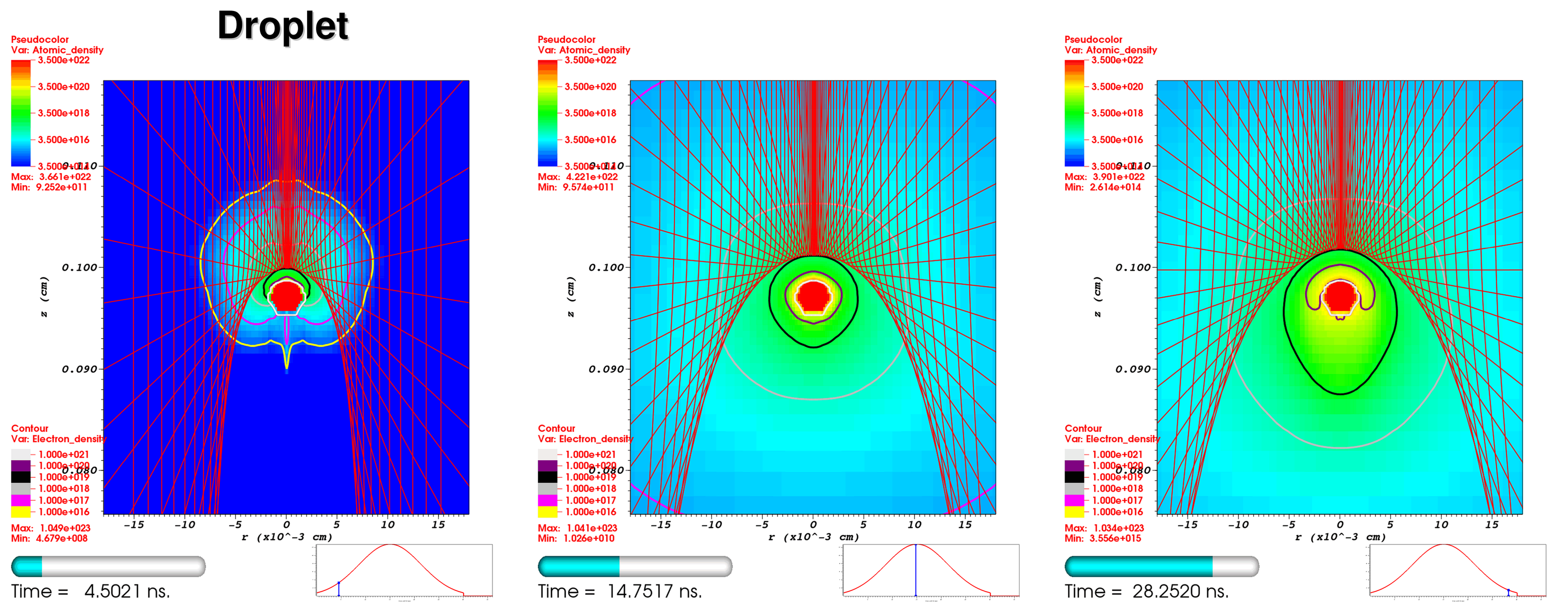
Cavern



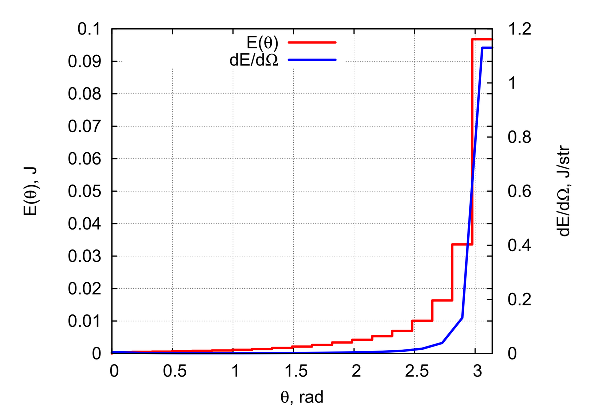
Target material – tin
CO_2 laser, 0.2 J:
•Gaussian time profile, FWHM = 15 ns
•Gaussian spatial profile, D = 300 μm (1/e²)



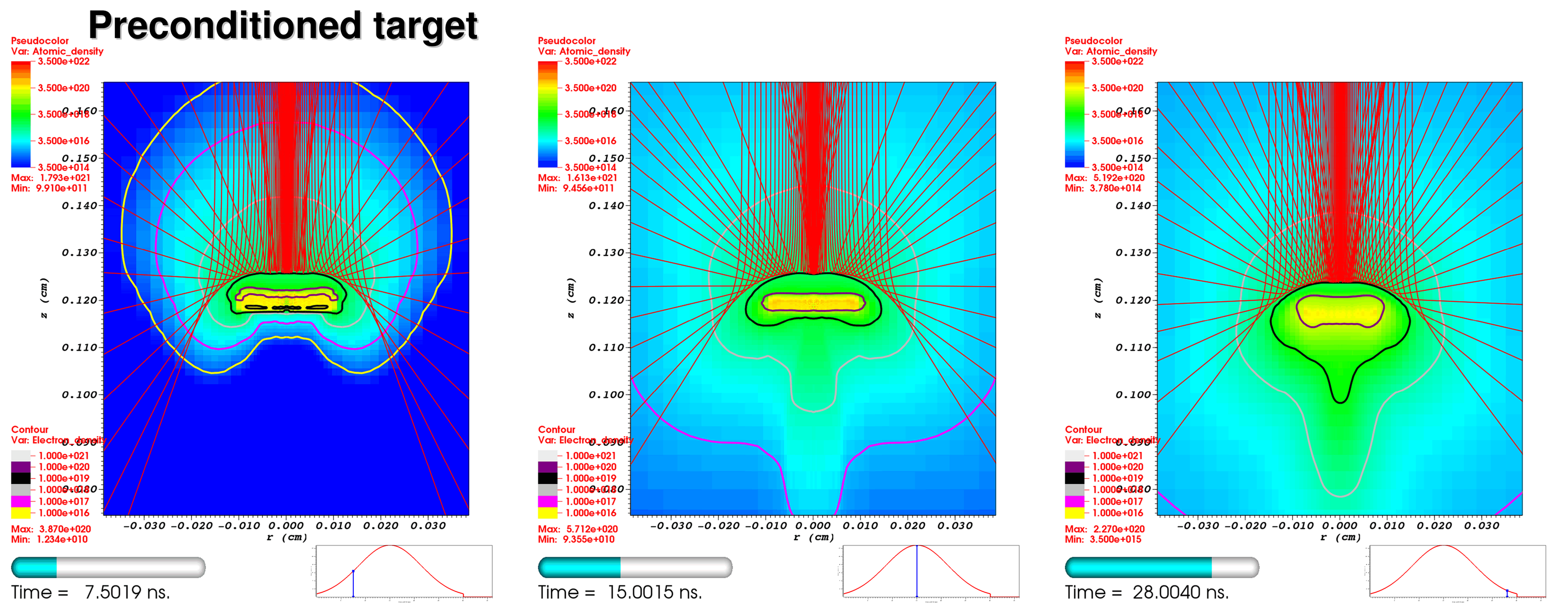
Droplet



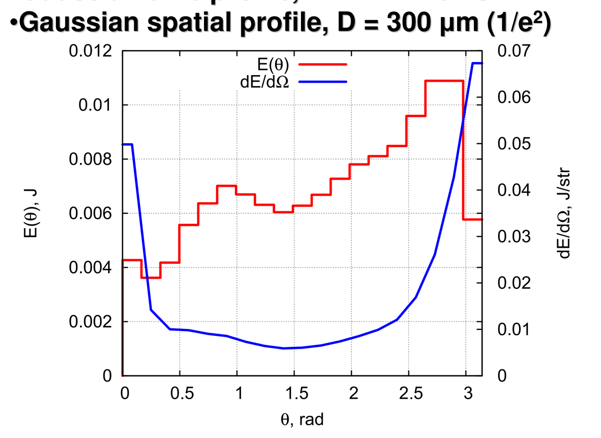
Target material – tin, diameter 30 μm
CO_2 laser, 0.2 J:
•Gaussian time profile, FWHM = 15 ns
•Gaussian spatial profile, D = 300 μm (1/e²)



Preconditioned target



Target material – tin:
•Initial mass – droplet, diameter 30 μm
•Initial geometry – D = 200 μm, h = 40 μm
•Characteristic fragment diameter – 1 μm
CO_2 laser, 0.2 J:
•Gaussian time profile, FWHM = 15 ns
•Gaussian spatial profile, D = 300 μm (1/e²)



Conclusions

•Simple and quite effective algorithm of laser tracing has been developed.
•Reasonable agreement with experimental data has been achieved.
•Easy generalization on 3D geometry is possible.
•The code can be used for in-line calculations as well as for postprocessing of an available RHD data.

Links and sources

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[2] *Tsygvintsev I.P., Krukovskiy A.Yu., Novikov V.G., Popov I.V.* Three-dimensional modeling of the laser radiation absorption in the geometrical optics approximation. Preprint of Keldysh institute of applied mathematics of RAS, 2012, №41, 20p.
[3] *Povarnitsyn M.E., Andreev N.E., Levashov P.R., Khishchenko K.V. and Rosmej O.N.* Dynamics of thin metal foils irradiated by moderate-contrast high-intensity laser beams. PACS numbers: 52.50.Jm, 52.38.-r, 79.20.Ds.
[4] *Ginzburg V.L., Rukhadze A.A.* The waves in magnetized plasmas, Nauka, Moscow, 1975.
[5] *Koshelev K.N., Ivanov V.V., Novikov V.G. et al.* RZLINE code modeling of distributed tin targets for laser-produced plasma sources of extreme ultraviolet radiation // Journal of Micro/Nanolithography, MEMS, and MOEMS. 2012. Vol. 11, no. 2. P. 021112–1–021112–6. URL:http://dx.doi.org/10.1117/1.JMM.11.2.021112